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Measurement of the Direct Effect of Sun-spots on Terrestrial Climates.

By Prof. S. P. Langley.

(*Communicated by E. Dunkin, F.R.S.*)

Since the question of the influence of Solar changes on Terrestrial climates was opened by the elder Herschel, a great number of Meteorological observations have been tabulated and discussed without the apparent attainment of any conclusive result, nor does there seem to be immediate hope of any solution from the study of such Terrestrial effects, while the evidence from these bears so different a meaning according to the interpretation of the compiler.

Though complete knowledge on this point seems still far beyond our reach, yet, if we consent to limit our enquiry to the *direct* effect of Sun-spots on the heat the Earth receives, there is, it seems to me, an untried means, which yields a sufficiently exact solution of the problem. It appears possible at least, to show (within certain definite limits) by how many degrees or parts of a degree Centigrade the Earth's mean annual temperature necessarily varies between a year of maximum and a year of minimum Spot-areas so far as the immediate effect of these on the solar thermal radiation is concerned.

To do this it is necessary,—

(1) To procure from experiment trustworthy measurements of the relative amounts of photospheric, penumbral, and umbral radiation.

(2) To determine the relative photospheric, penumbral, and umbral surfaces, in a maximum and in a minimum year, and (having suitably combined these data) to

(3) Show within what specific limits we can assert that the Terrestrial temperature will be necessarily changed.

The first condition, is so far as I know, heretofore unsupplied, owing to the experimental difficulties which have only lately been overcome. The results of recent measurements at the Allegheny Observatory now published for the first time will furnish these data.

For the second condition, I shall avail myself of the published results of Schwabe, Carrington, De La Rue, and others.

For the third, a method will be employed which, if in some measure novel, is apparently a legitimate deduction from facts in themselves not open to question.

1. *Direct Thermal Measurements of Solar Radiation.*

Since the original observations of Henry, in 1845,[*] established the important fact that the thermal radiation of a spot is in general

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[*] *London, Edinburgh, and Dublin Philosophical Magazine*, 3rd Series, 1846, p. 230; Poggendorf's *Annalen*, 1846, vol. 68, p. 102.

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less than that of the photosphere, nothing appears to have been added to show by how much it differs. If quantitative results have, in spite of their obvious value, never been obtained, it is doubtless owing to the experimental difficulties we meet in passing from the point at which we can say that the spot-radiation is less, to that at which we can say with confidence *how much* it is less. To but partially indicate the nature of these difficulties, we may observe that the umbra of a sun-spot occupies so small an area, that the quivering of the telescopic image, due to atmospheric tremor, commonly causes its libration through a range on either side of its mean position exceeding its own semi-diameter. Whatever the size and stability of the telescope, or whatever the enlargement of the image, or the minuteness of the thermopile we seek to expose only to umbral heat, penumbral radiations will then be registered to some extent, or if it be penumbral radiation we would observe, umbral and photospheric heat will alternately enter with it. This is no serious drawback, if we seek to show only, that the spot as a whole is cooler or hotter without enquiring in what degree; but obviously it is fatal to accuracy, when we would determine by how much the radiation is diminished by each part. We must either take the telescope beyond the limits of our lower atmosphere then, or observe only in those rare and brief periods when the image is still. These periods in our northern climates are always associated during the day with the presence of moisture and haze in the atmosphere. It is almost superfluous to remark that these conditions, which secure a tranquil image, are precisely those most unfavourable to the transmission of radiant heat, and the excessively diffuse and enfeebled rays which form the enlarged image, are, in spite of every precaution, apt to be confused with radiations which reach the pile from extraneous sources.

Trials were made in 1873 and 1874 of a great many plans, for so shielding the pile that it might be absolutely protected against every source of disturbance except the minute pencil of umbral or penumbral rays, with incomplete success, till in the close of the latter year an apparatus was devised by the writer with which, though the time for large spots was passed, satisfactory measures were at last obtained.

The apparatus cannot be fully explained without illustration; the essential conditions of success, however, are that to an eye placed in the position of its working face the part of the spot to be studied and the blackened walls of a chamber surrounded by water at a constant temperature are alone visible, and that provision is yet made for the observer's ability to verify at any moment the position of the image projected on this hidden face, which is maintained at all times in the optical axis. The pile specially constructed by the late Mr. Becker is composed of very minute elements and used in connection with a reflecting galvanometer. The use of a large Equatoreal with accurate clock-work is of course presupposed. That employed was a refractor (and

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it will hence be understood that our measurements are confined to luminous heat rays), having an aperture of 13 inches. The projected image was formed on a scale of from four to eight feet to the solar diameter.

The pile was ordinarily first placed in the image of the photosphere, between the spot and the centre of the disk, and the galvanometric deflexion noted; next an exposure of equal length in the umbra was made, and then the observation once more repeated with the pile in the adjacent photosphere between the spot and the limb. The mean of the photospheric readings, after the instrumental reductions are applied, is used as a divisor for the (reduced) umbral reading. The quotient expresses the value of the umbral radiations, in parts of those of the adjacent photosphere. The decrement of heat, as we approach the limb, is, though not exactly, yet so very nearly, in the same ratio for photosphere and spots, that no correction is needed on this account for the present observations. Thirty-six measurements on Umbræ, and thirty-two on Penumbræ, were obtained in the autumn of 1874 and the spring of 1875, as follow:—

Umbral Heat-radiation (Photospheric Radiation = 1·00).	Penumbral Heat-radiation (Photospheric Radiation = 1·00).
0·55	0·86
0·43	0·74
0·49	0·92
0·49	0·98
0·55	0·80
0·61	0·68
0·61	0·82
0·53	0·80
0·55	0·84
0·63	0·73
0·57	
0·50	0·74
0·49	0·83
0·53	0·84
0·54	
0·49	0·75
0·53	0·73
0·57	0·84
0·57	0·79
0·61	0·69
0·52	0·71
0·49	0·81
0·51	0·77

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Umbral Heat-radiation (Photospheric Radiation = 1·00).	Penumbral Heat-radiation (Photospheric Radiation = 1·00).
0·54	
0·59	0·89
0·54	0·83
0·52	0·62
0·47	0·82
0·60	0·74
0·53	0·74
0·47	0·82
0·52	0·74
0·52	0·96
0·54	0·89
0·54	0·89
0·58	
Mean 0·54 ± 0·05	Mean 0·80 ± 0·01

The result is, that taking the mean thermal photospheric radiation in the spot's vicinity as unity, the mean Umbral radiation is fifty-four one-hundredths (with a probable error of five one-thousandths), the mean Penumbral radiation eighty one-hundredths (with a probable error of one one-hundredth). These errors include all discrepancies due to the greater or less approach to the limb in the spots measured, or due to absolute differences in their radiation, as well as the errors of observation.

(2.) *Comparison of Umbral and Penumbral Areas in a year of maximum with those in a year of minimum.*

To determine the spotted area of the disk in years of maximum and of minimum, I have taken from a paper by Messrs. De La Rue, Stewart, and Loewy, in the *Philosophical Transactions* ('Researches in Solar Physics,' No. 2, page 115), the following dates:—

Maximum	Dec. 31, 1836	Minimum	Sept. 21, 1843
„	Nov. 14, 1847	„	April 21, 1856
„	Sept. 7, 1859	„	Feb. 14, 1867

In the same Memoir, under Table 8, is given for every 14th and 28th day of the month from 1832 to 1868, the total spot-area in millionths of the Sun's visible hemisphere, deduced from the observations of Schwabe, Carrington, and the authors; and, by addition of the fortnightly means, we obtain the following annual ones for three years of maximum and three of minimum:—

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For 6 months preceding and 6 months following	Dec. 28, 1831	Spot area =		·034670
,, ,,	Sept. 21, 1843	,, ,,	·002555	
,, ,,	Nov. 14, 1847	,, ,,		·031055
,, ,,	April 28, 1856	,, ,,	·000850	
,, ,,	Sept. 14, 1859	,, ,,		·034530
,, ,,	Feb. 14, 1867	,, ,,	·002115	
			·005520	·100255

Whence we find the mean spot-area at any time in a year of maximum = ·001392, in a year of minimum = ·000077; figures which are deduced from a large number of spots distributed with approximate uniformity in longitude, and which hence represent not alone the total spot-area in part of the visible hemisphere, but the total apparent area in parts of the visible disk.

From an enumeration of every Umbral and Penumbral measurement recorded by the authors, from February 7, 1862, to December 31, 1863, we obtain—

$$\frac{\text{Mean Umbral Area}}{\text{Mean Spot Area}} = \frac{21371}{79747} = \cdot 27 ;$$

$$\frac{\text{Mean Penumbral Area}}{\text{Mean Spot Area}} = \frac{58377}{79747} = \cdot 73 .$$

These figures obtained from observations made at a period midway between a maximum and a minimum doubtless represent with approximate truth the relative Umbral and Penumbral areas at other periods. Hence, we conclude that the

Mean Apparent Umbral Area in a year of Maximum = ·001392 × ·27 = ·000376
,, Penumbral ,, ,, = ·001392 × ·73 = ·001016
,, Umbral ,, Minimum = ·000077 × ·27 = ·000021
,, Penumbral ,, ,, = ·000077 × ·73 = ·000056

We have now to multiply each area by its measured rate of thermal radiation already found. Thus, we obtain

·000376 × ·54 = ·000203
·001016 × ·80 = ·000813
·001016

·000021 × ·54 = ·000011
·000056 × ·80 = ·000044
·000055

and since it thus appears that the average spot-radiation earthwards in a year of maximum is ·001016, and in a year of minimum ·000055 of that of the apparent disk, it follows that the total effect of the spots in diminishing the solar radiation by the diminished heat from the increased area they periodically occupy, will not exceed the difference of these numbers or

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·000961. The figure in the sixth decimal place having no real significance, and that in the fifth being doubtful, we may say that the greatest admissible direct effect of the spots is to diminish the Sun's thermal radiation by a quantity somewhat less than $\frac{1}{10}$ and somewhat greater than $\frac{1}{11}$ of one per cent.

(3) *Limits within which Terrestrial Temperature will be affected by such Changes.*

An exact computation of the effect of the Solar radiations on Terrestrial Temperatures requires a knowledge of the heat the Earth receives from other than solar sources. A number of eminent Physicists have attempted to determine this, but with results which are so discrepant that we can feel, as it seems to me, little confidence in their use. The method here adopted, will not assume any knowledge as to the "temperature of space," or any of the other as yet indeterminate factors, indispensable to a complete solution of the problem: we shall therefore not attain an exact result; but we shall be able to feel confident that we can say with assurance within what limits the truth must lie.

There seems to be no question that a temperature as low as $-56°$C. has been observed in the open air of the Arctic regions, and it is plain that were the Sun's heat altogether withdrawn, the mean Terrestrial temperature would fall at least as low. Independently of stellar radiation, the Earth receives at the upper limit of its atmosphere a certain amount of heat from non-luminous interplanetary matter, which has absorbed and is radiating obscure heat originally derived from the Sun. Computations of the amount of this obscure radiation indicate that it is more considerable than might be supposed; but as little value attaches (it seems to the writer) to such estimates, they are referred to, only to enforce the statement that were the Sun's heat wholly cut off, whatever the mean temperature the Earth might attain it would certainly be below $-56°$C., and as its actual mean actual temperature is estimated at from $+14°$ to $+16°$ Centigrade, it is clear that to the entire solar thermal radiations not less than 70° C. of our actual temperature is due.

The least change in solar heat due to the cause we discuss being, as has been shown, $\frac{1}{10}$ of one per cent. of the whole radiation, whose thermometric effect registered here is a change of at least 70°C. we find $\frac{0°\cdot 7}{11} = 0°\cdot063$C. as the *least* change in Terrestrial temperature which we can attribute to the direct effect of the spots.

Again, since the Earth can in no circumstances part with more heat than it possesses, we may, taking the absolute zero as at

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$-274°$ C. say that $16°+274°=290°$ C. represents the greatest effect we can assign to the Sun, and that since the greatest change in solar radiation due to the spots is shown to be less than $\frac{1}{10}$ of one per cent. $\frac{2°\cdot 9}{10} = 0°\cdot 29$ C., is the *greatest* change in Terrestrial temperature which can be due to this cause.

In all that has preceded it has depended on certain data drawn from observations made by means which exclude the measurement of the thermal effect due to rays in the ultra-red and ultra-violet parts of the spectrum, but were these obtainable, there seems no probability that these conclusions would be materially affected.

To prevent misapprehension, let it be repeated that nothing is here given as being to the writer decisive of the question—whether Terrestrial temperature may not be quite otherwise affected by some varying Solar action of which spots are merely accompaniments—and then, with this understanding, we may reach the following conclusion:—

Sun-spots do exercise a direct and real influence on Terrestrial climates by decreasing the mean temperature of this planet at their maximum. This decrease is, however, so minute, that it is doubtful whether it has been directly observed or discriminated from other charges. Its whole effect is represented by a change in the mean temperature of our globe in eleven years, not exceeding three-tenths, and not less than one-twentieth, of one degree of the Centigrade thermometer.

Allegheny Observatory, Allegheny, Pa.,
1876, *June* 16.

Observations of the Solar Eclipse of 1876, *September* 17.

By John Tebbutt, Esq.

The atmosphere was calm and clear. At the time of first contact the Sun was low, but the undulation along the limb was not so great as I expected; this phase was, therefore, pretty well observed. The observation of the last contact was very satisfactory. The following are the Observatory local mean times of observation:—

		d	h	m	s
First contact	Sept.	17	18	22	2·6
Last ,,		,,	20	1	34·3

The Sun being hidden from the 4½-inch Equatoreal by the house and trees, the eclipse was observed by means of the 3¼-inch portable refractor armed with a power of ninety and a green shade. The position of the telescope was about sixty yards east